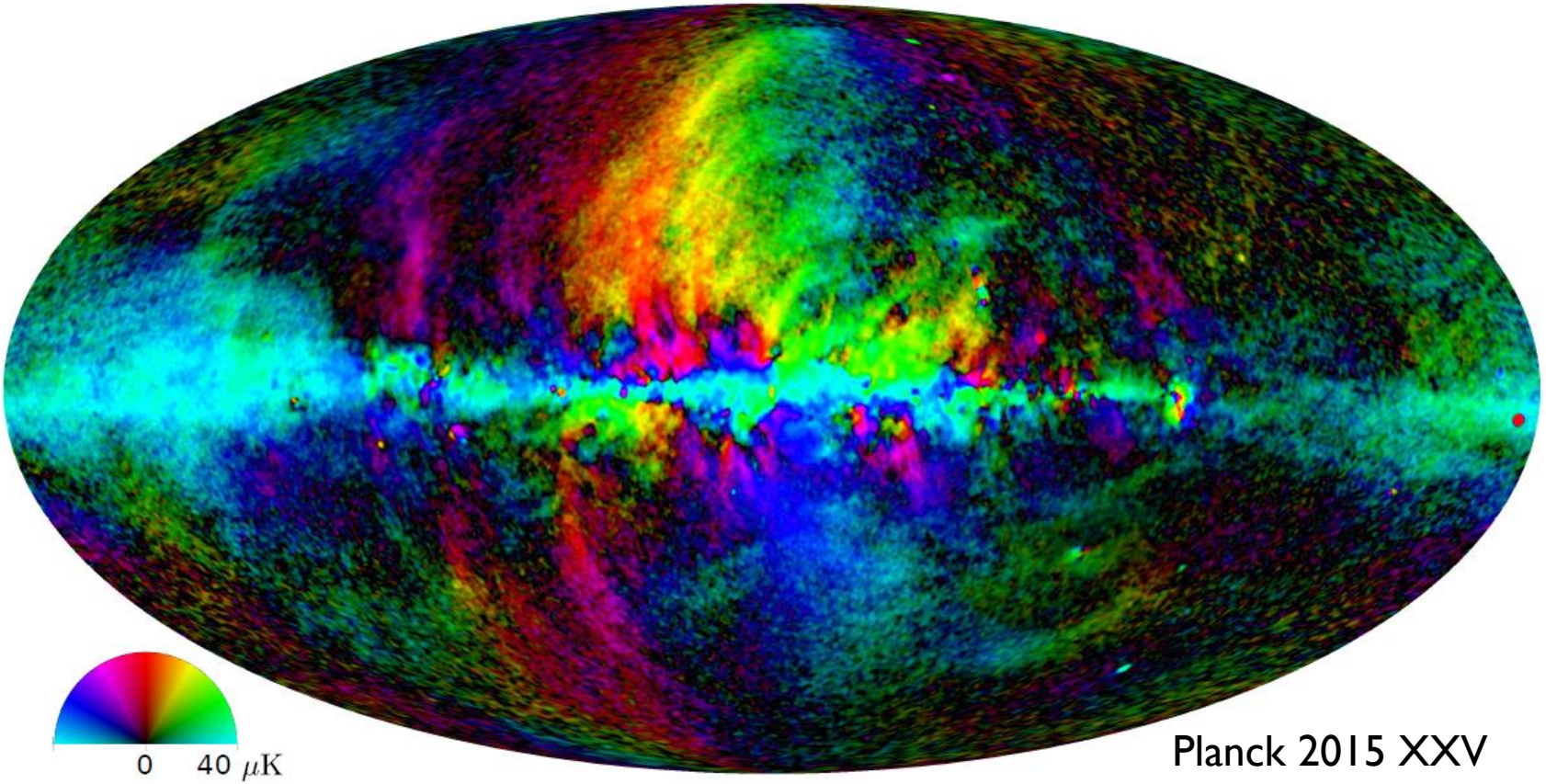
Synchrotron Foregrounds for B-modes

Paddy Leahy



Planck 2015 XXV

Overview

- A bit of synchrotron theory (and practice)
- Synchrotron foregrounds at low frequency
- Faraday rotation of the Galactic Synchrotron emission
- Angular power spectra of the polarized synchrotron foreground and sychrotron structure
- Zero levels

Discovery

"All the News That's Fit to Print."

The

VOL. LXXXII....No. 27,495. Entered as Second-Class Matter, Postoffice, New York, N. Y.

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and

Flier Asks Blame in Crash, But Inquest Absolves Him

By The Canadian Press.

LONDON, May 4.—A chivalrous attempt to assume responsibility for the fatal crash of a Royal Air Force plane on May 1, in which Viscount Knebworth, pilot, and Aircraftman Harrison lost their lives, was made by Flight Lieutenant Eric Hobson at the inquest today. Despite Lieutenant Hobson's action, a verdict of "death due to misadventure" was returned.

Lieutenant Hobson, the leader of the section of which Lord Knebworth was a member, described how he unaccountably lost his height and at the end of a 2,000-foot dive got dangerously near the ground.

"The error in judgment was certainly not due to carelessness or recklessness," said Lieutenant Hobson, adding that Lord Knebworth was "absolutely blameless for what had happened, but had simply followed him according to orders."

KIDNAPPERS URGED TO ANSWER PLEAS

New Yorker Named to Act as Secret Agent for Return of McMath Child.

BIG NEW INV... PLANNED BY ... ON ROAD TO...

Larger-Scale Offer... Last Is Announced Soon in North...

CHIANG RUSHES A...

Famous Units That ... Shanghai Are Di... to Help 50,000 ...

BRITISH QUIT M...

Concerns Assert the ... Commerce Is Bein... Shut Against Fo...

By HALLETT A...

Wireless to The New Y...

TIENTSIN, May 4.—... vealing Japan's plans ... military incursion in ... an official spokesman ... quarters of the mili... said today:

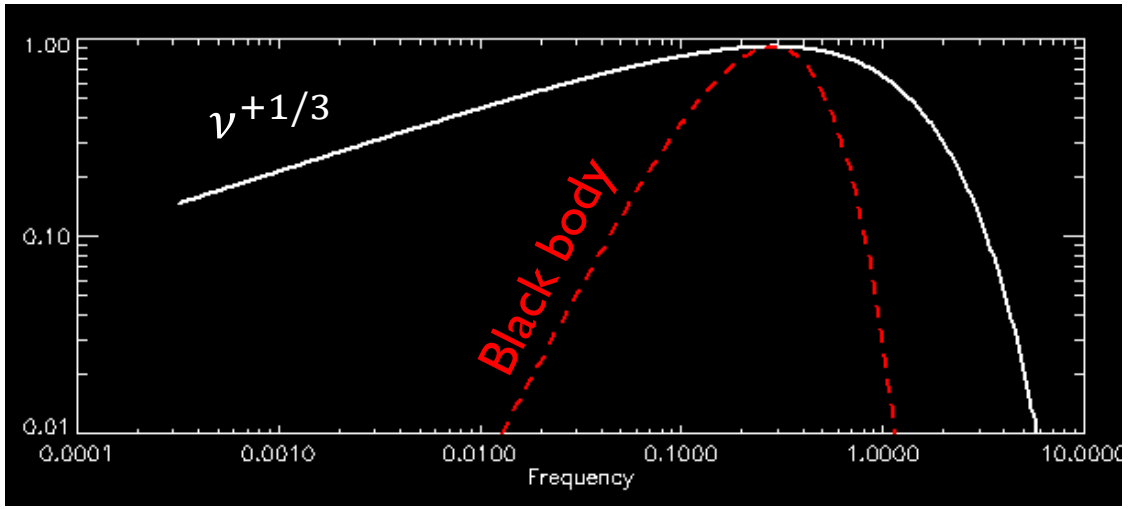
- Explanation followed later:

- I. S. Shklovsky, 1953

Theory reminder

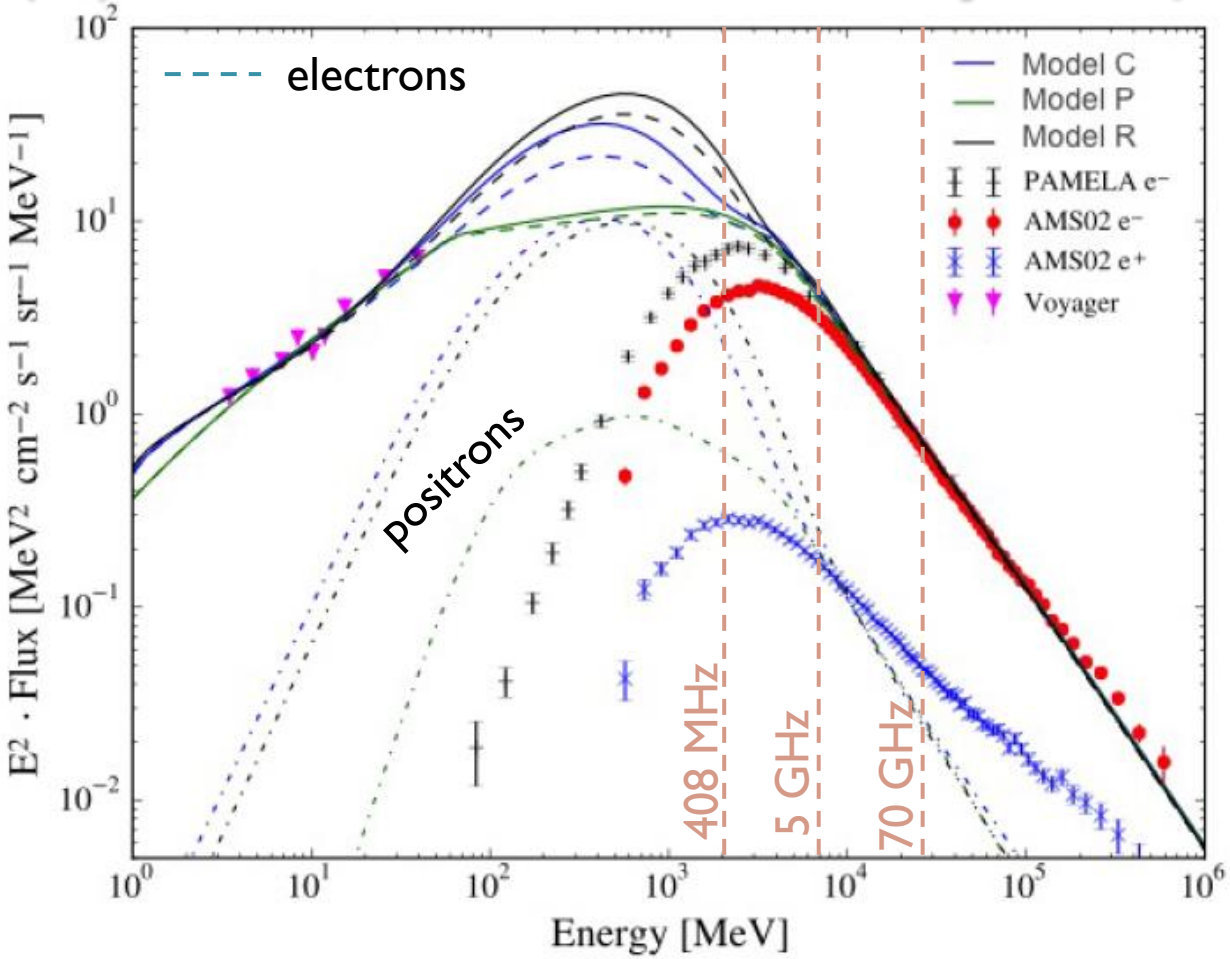
- For uniform magnetic field, synchrotron emission spectrum is convolution of mono-energetic synchrotron spectrum $F(\nu/\nu_c)$ with cosmic ray lepton spectrum:
- $j_\nu = kB \int N(\ln E) F(\ln \nu - 2\ln E - \ln B)\, d\ln E$

F



- NB: $\nu \propto E^2$: One decade in frequency is only factor of 3 in particle energy
- Variations in B further smooth spectrum

$N(E)$: Local Cosmic Ray e^-/e^+

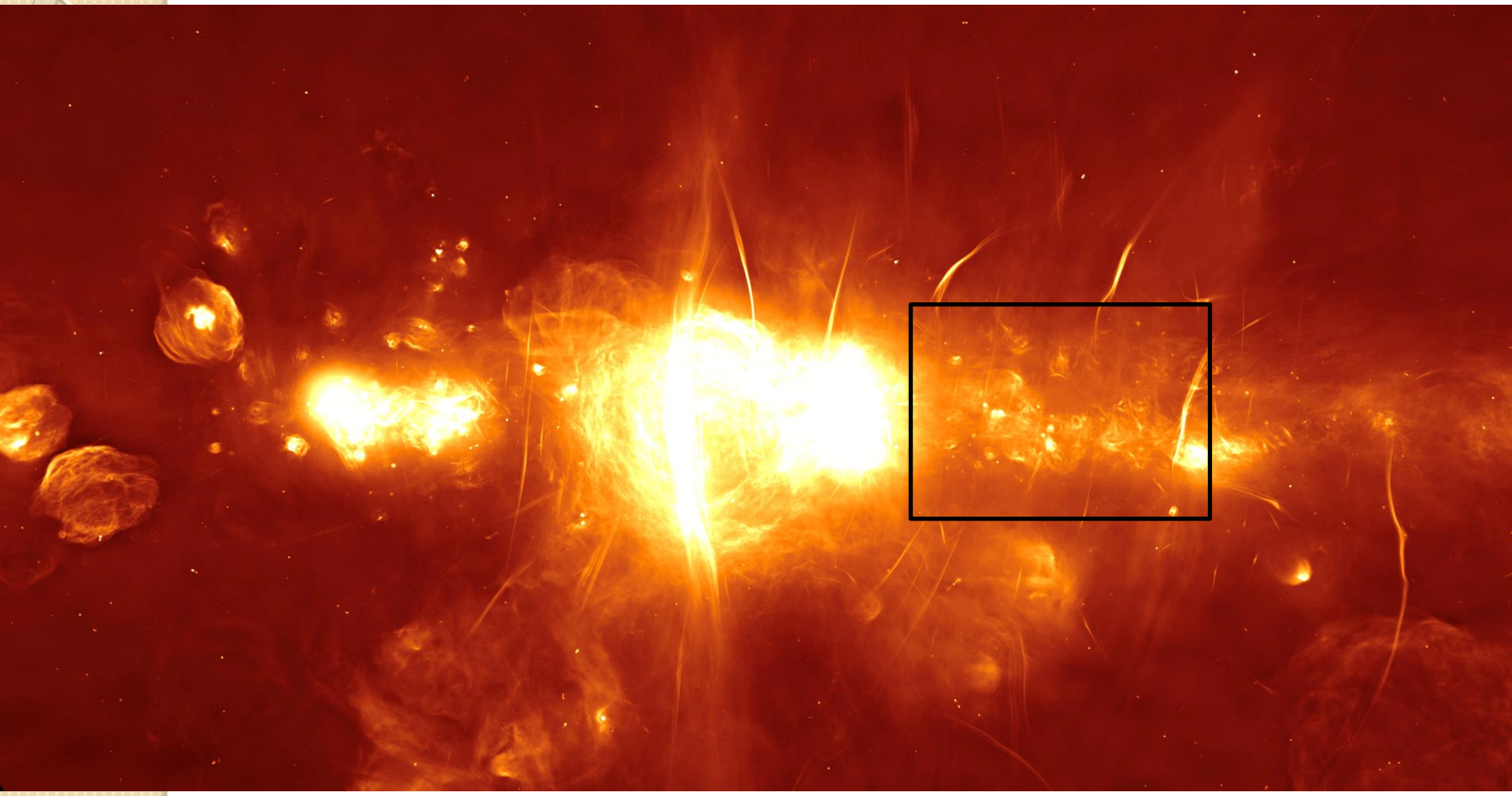


- Orlando et al. ICRC 2017
  - Equivalent frequencies for 6 μG field

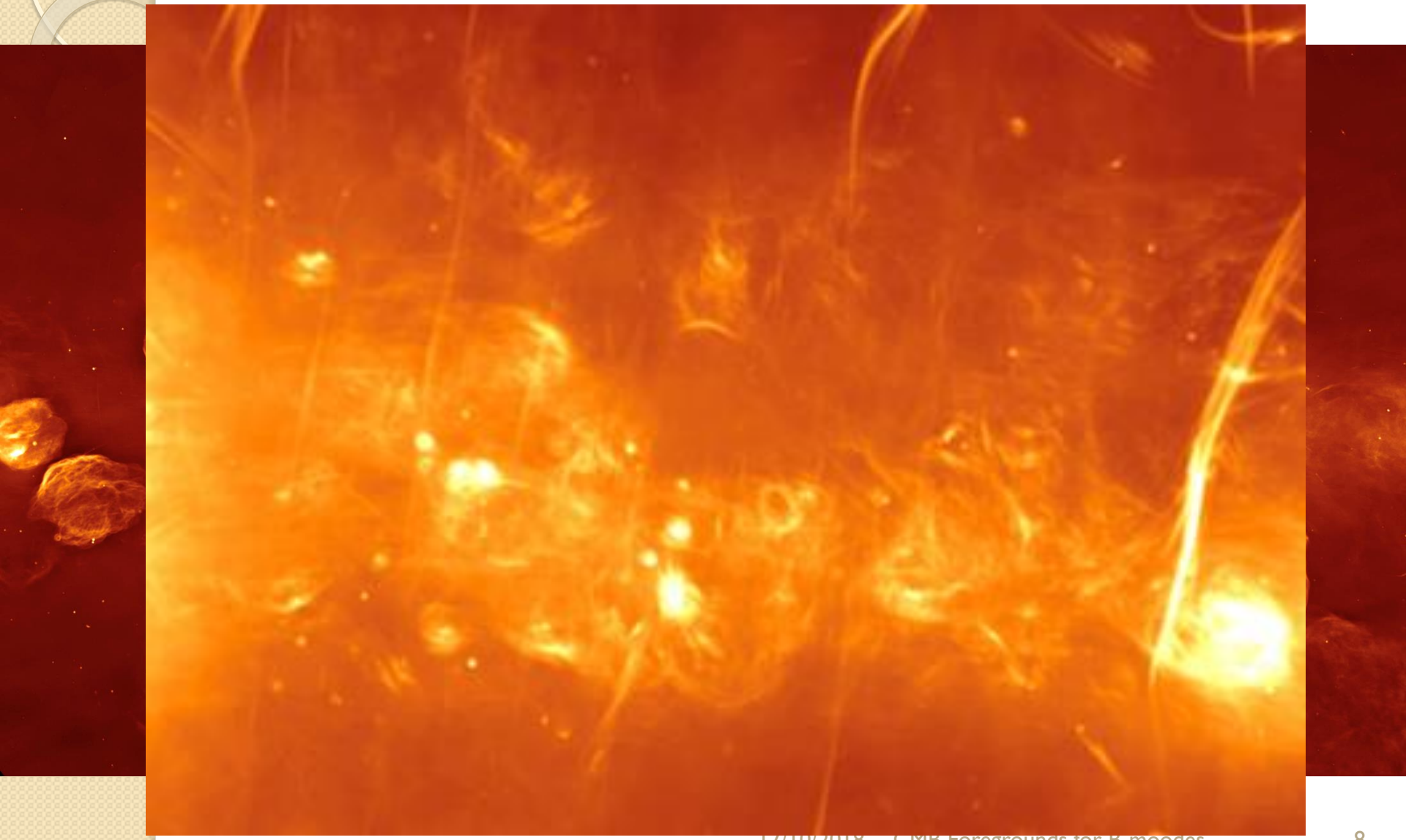
Synchrotron spectra

- Bad news: Synchrotron spectra are not power laws
- Good news: Syncrotron spectra are extremely smooth:
  - pretty safe to extrapolate over factor of a few in frequency.
- Good news: Synchrotron spectra in the Milky Way ISM are remarkably uniform

Galactic Centre from MeerKAT

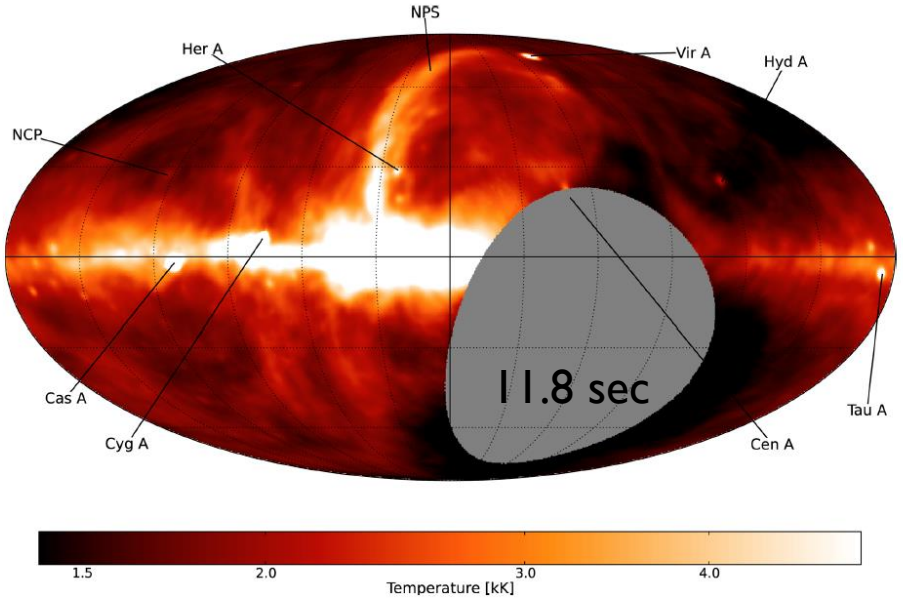


Galactic Centre from MeerKAT



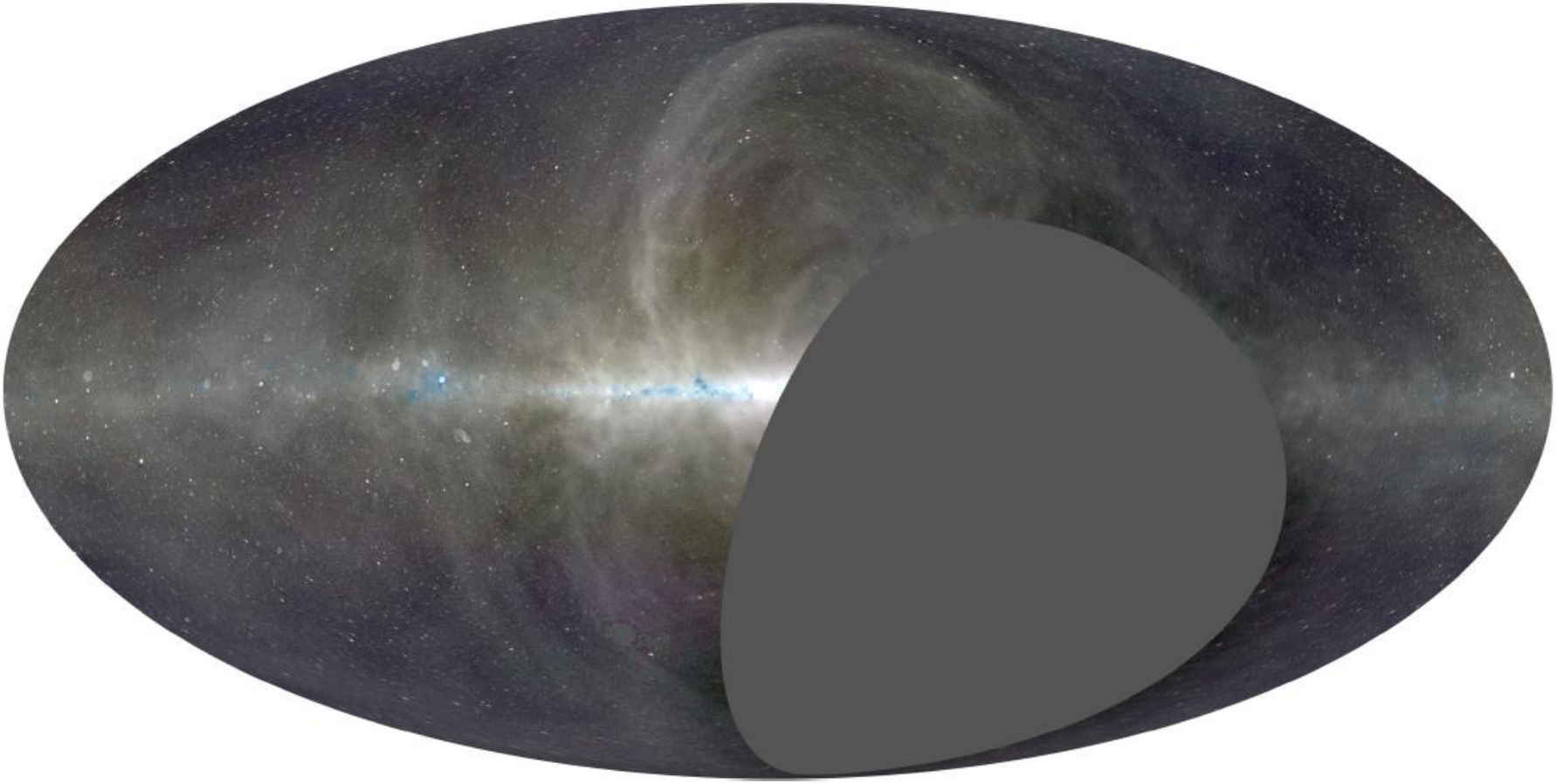
New surveys at low frequency

- LWA (New Mexico):
  - 35-85 MHz, ≈ 3° FWHM
  - Dowell et al (2017, MNRAS)
- LWA (OVRO):
  - 37-73 MHz 15 arcmin FWHM
  - Eastwood et al (2018, AJ)
- GLEAM (MWA)
  - 88-215 MHz, ~2 arcmin FWHM
  - Hurley-Walker et al (2017) etc.
  - Galactic plane data not yet released



- EoR-oriented experiments.
- Reproducibility at 10-25% level.

LWA-OVRO 37/52/73 MHz



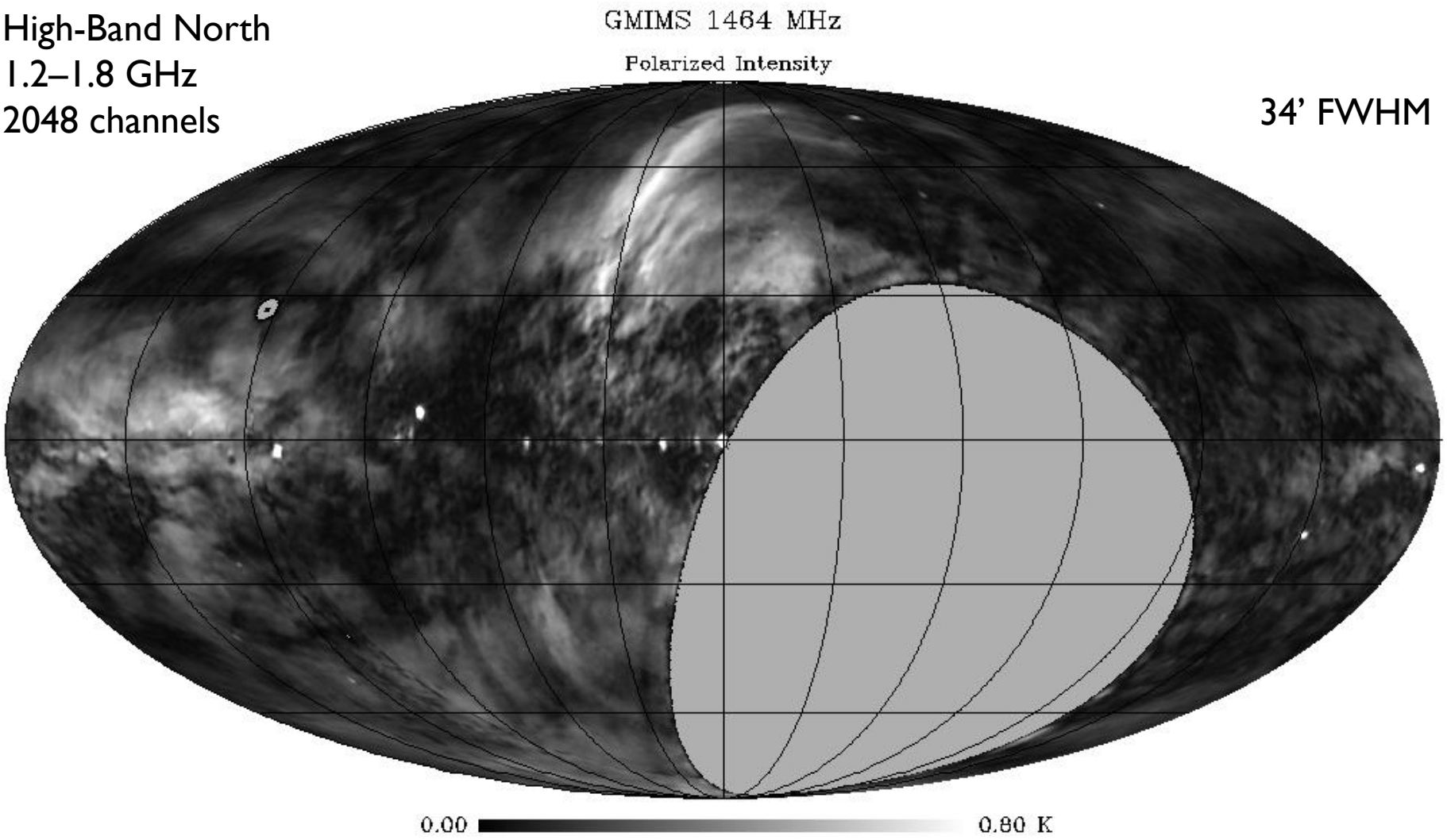
White: $\beta = 2.5$; Red: steeper, Blue: flatter

New surveys: Faraday rotation

- Global Magneto-Ionic Medium Survey (GMIMS)
- Ambition:
  - All-sky, IQU(V)
  - 300-1800 MHz
  - ≈1° FWHM
- Realised:
  - High-band North: Penticton, 1280-1750 MHz
    - Wolleben et al (2010); Sun et al (2015); Hill et al (2017)
  - Low-band South: Parkes, 300-480 MHz
    - Wolleben et al in prep.
- In the can: HBS (Parkes)
- GALFACTS
- Arecibo L-band Feed Array
  - 1225-1525 MHz
  - 3.5 arcmin FWHM
- 0.9°-36.7° = 30% of sky
  - All sky visible to Arecibo.
- Current status:
  - Reasonable-quality maps for 1367-1525 MHz

Global Magnetoionic-Medium Survey

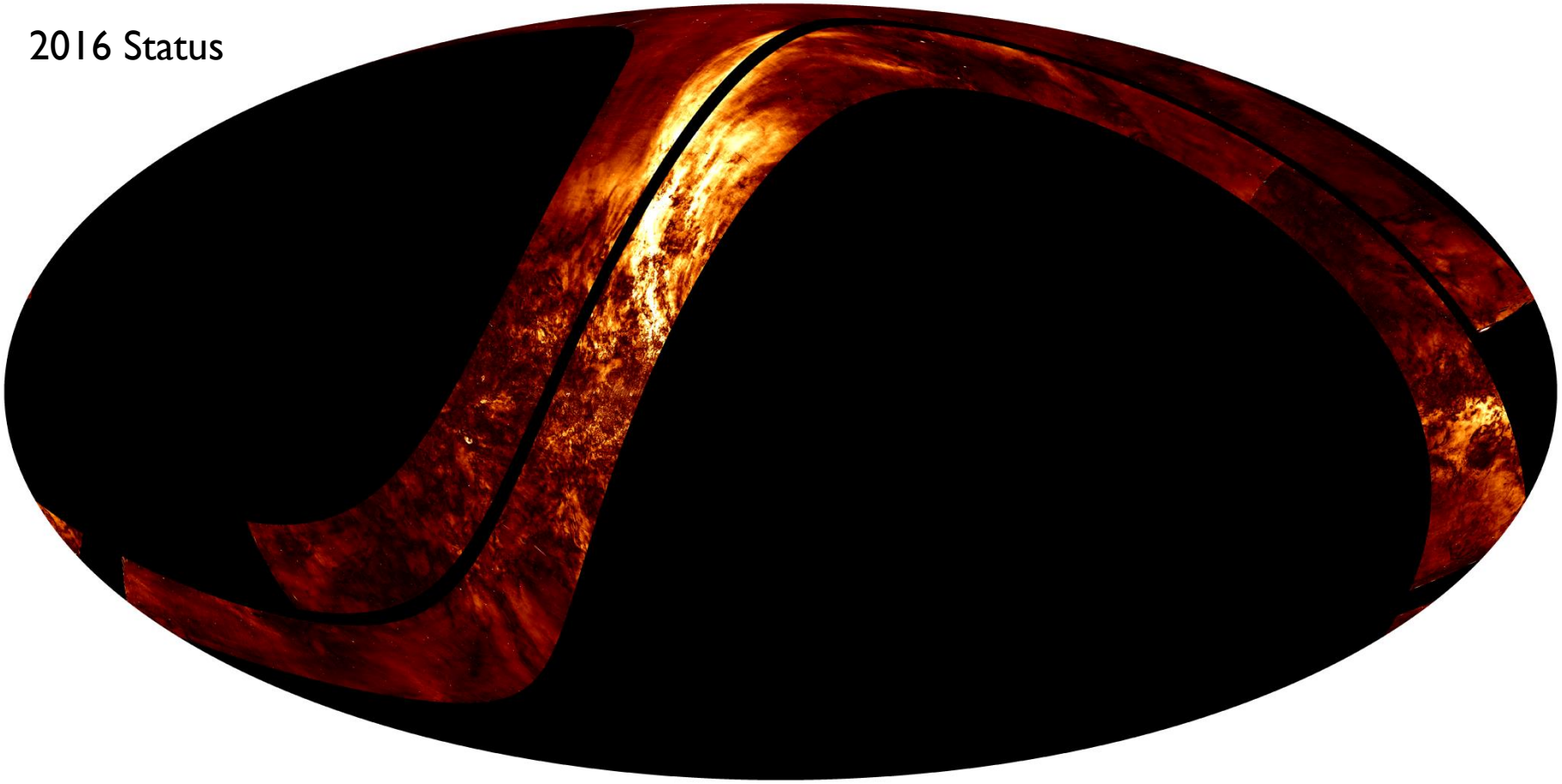
High-Band North
1.2–1.8 GHz
2048 channels



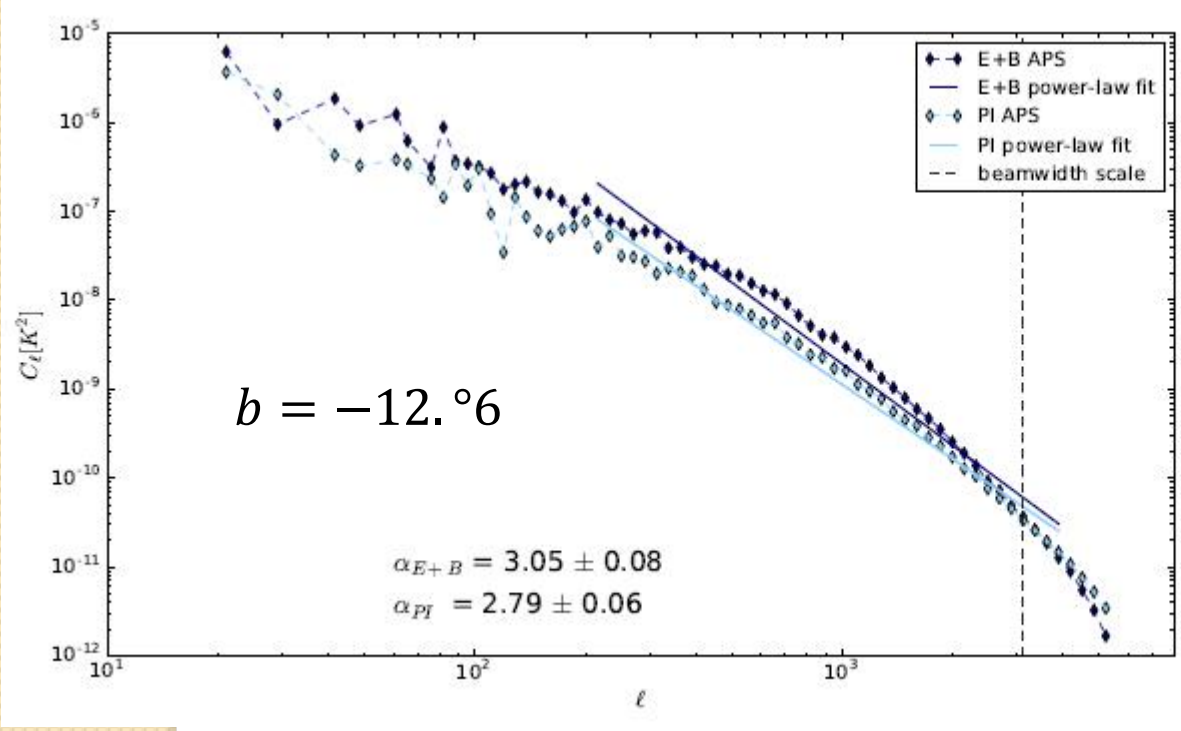
34’ FWHM

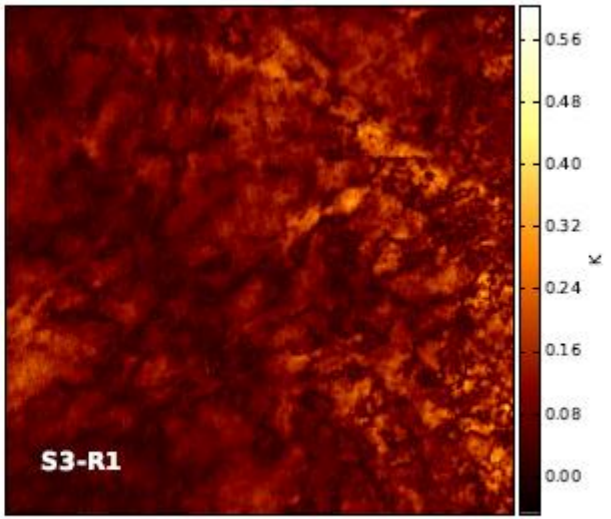
GALFACTS polarization

2016 Status



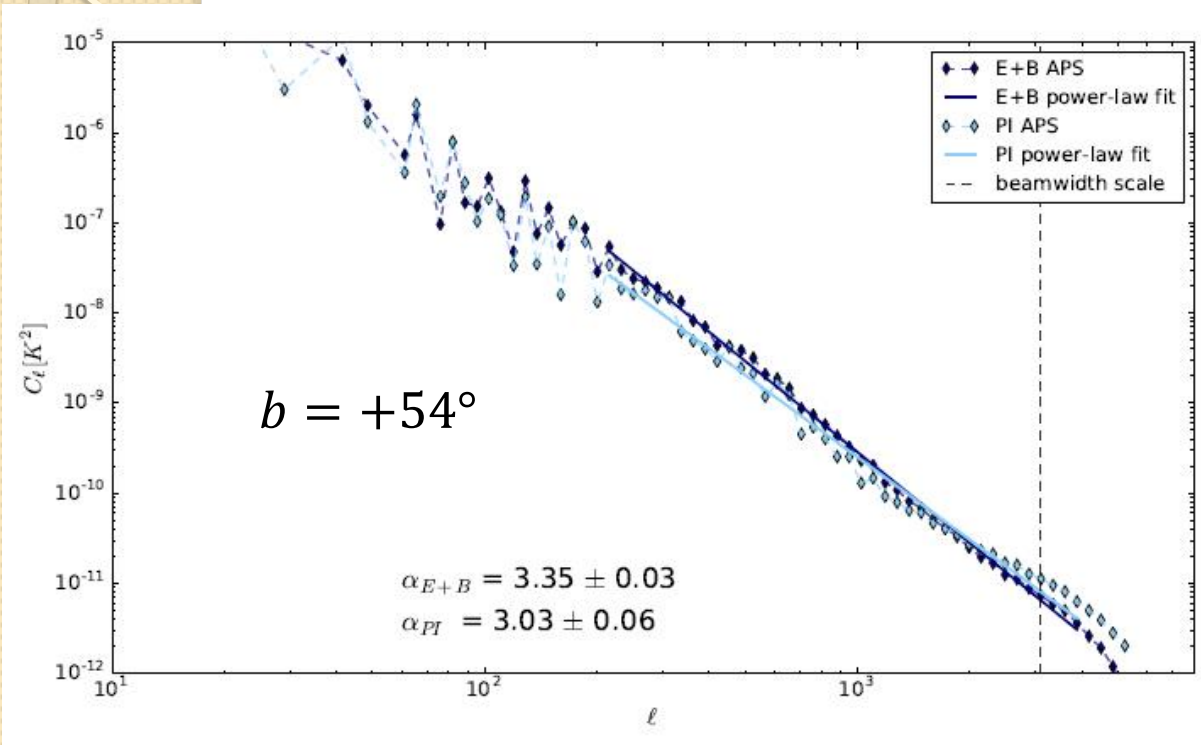
GALFACTS Synchrotron APS

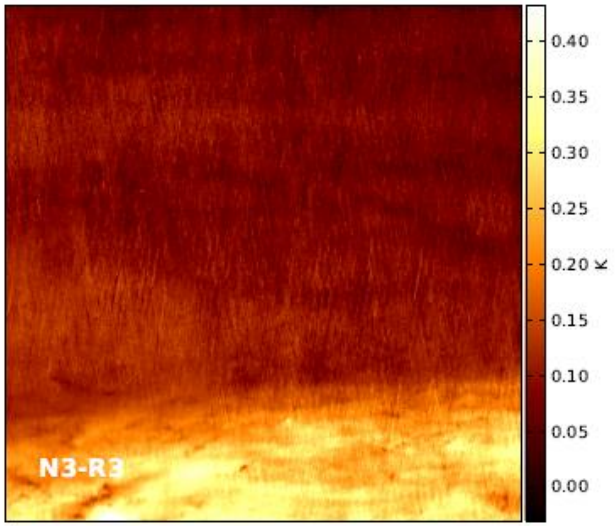




- From Indy Leclercq (2017, PhD thesis)
- 15°× 15° region

Sample results

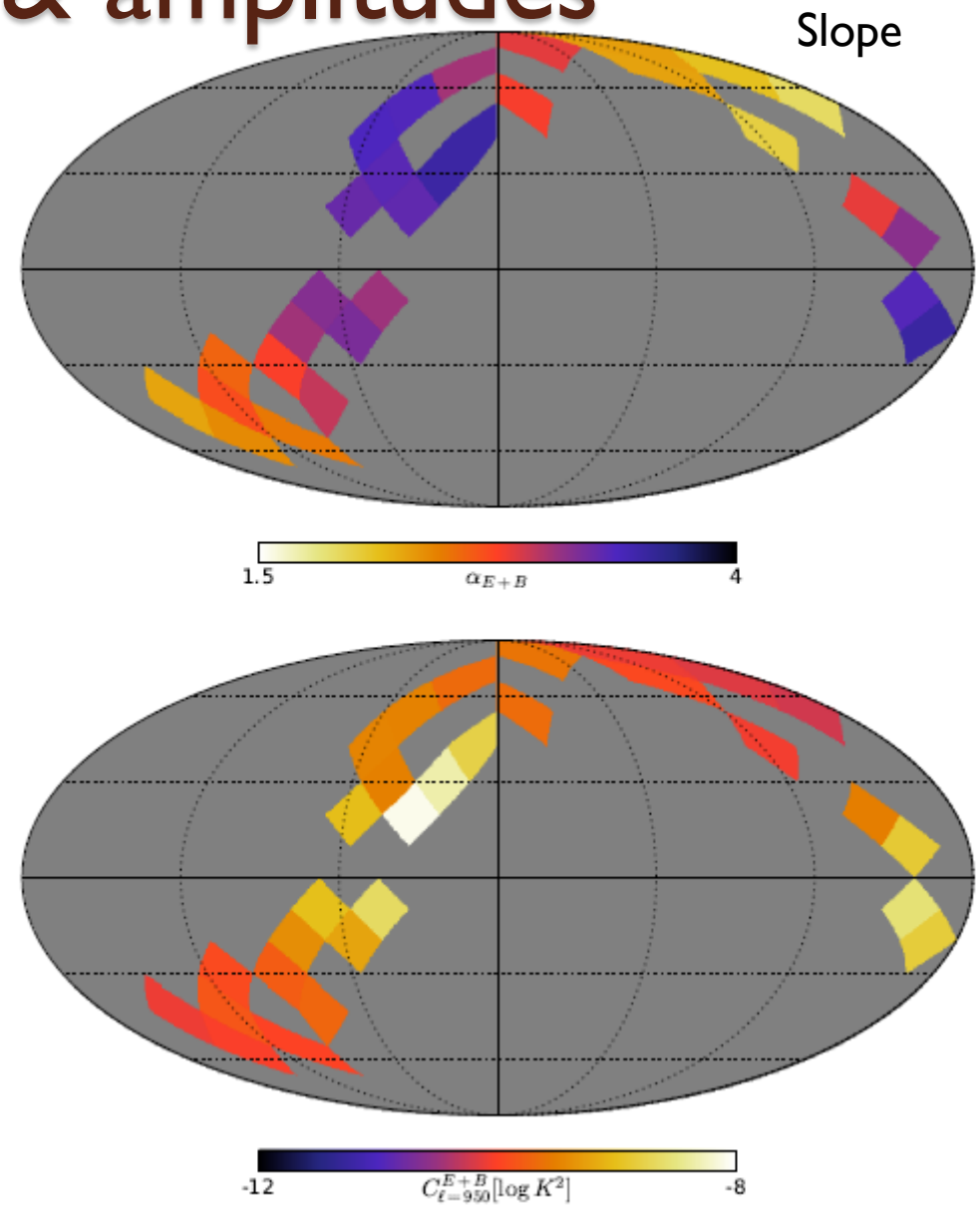




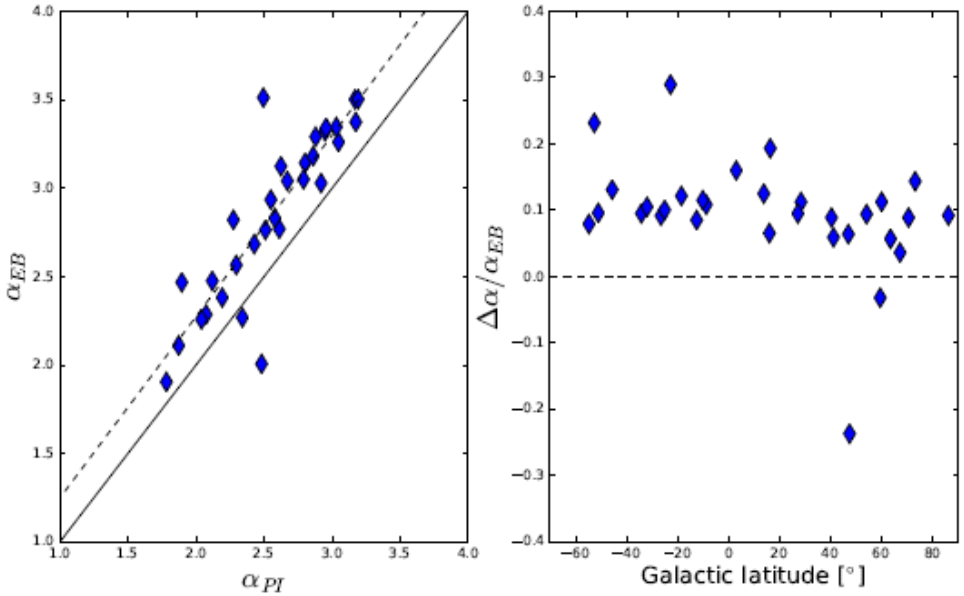
- Edge of NPS

Fitted Slope & amplitudes

- We analysed 31 15°×15° fields, excluding highly depolarized regions near the plane, & a few missing fields.
- Fitted power law to C_l for $220 < l < 4200$
- Both power law index and amplitude vary substantially across the sky, i.e. no universal synchrotron angular power spectrum.

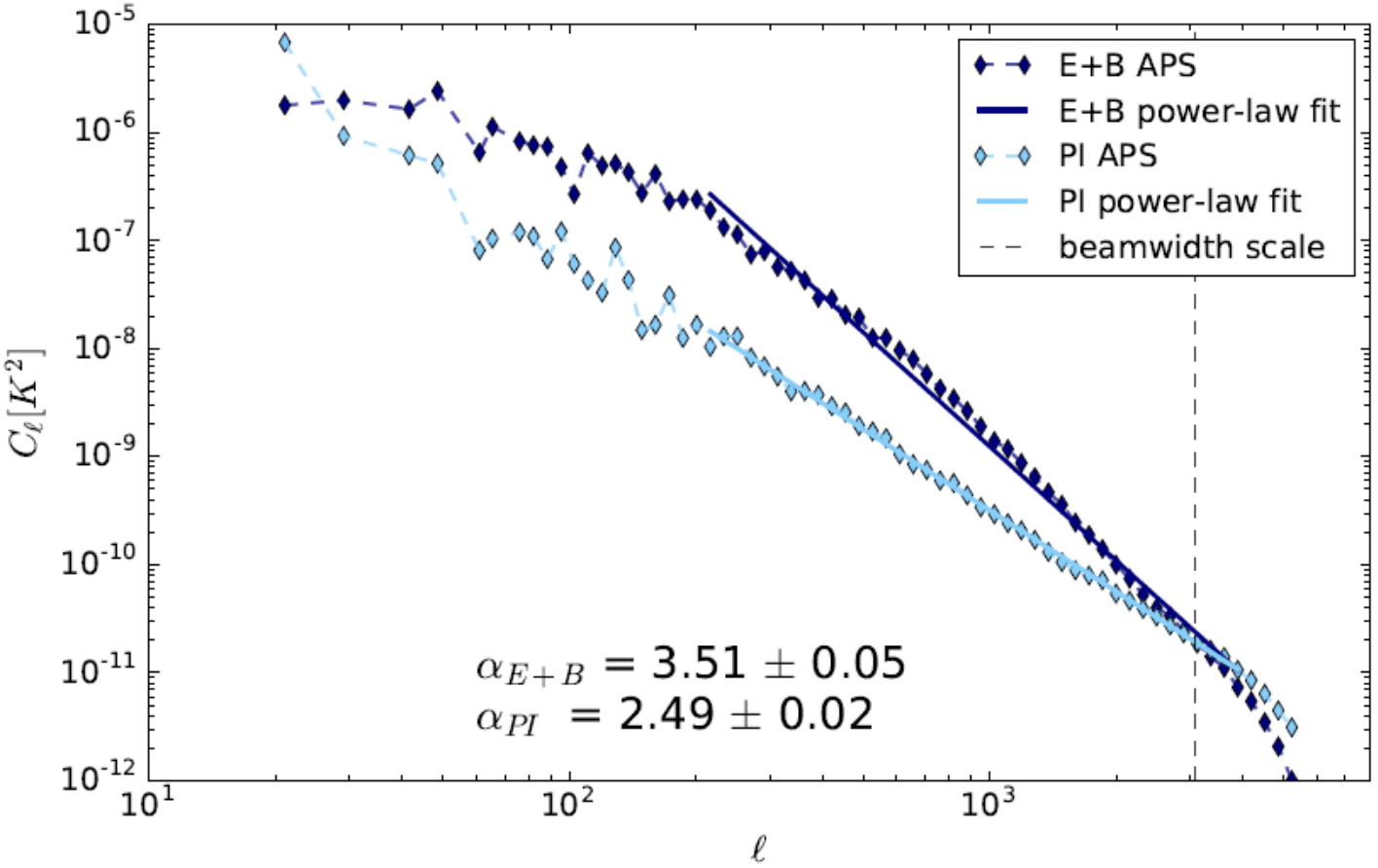


Comparison with Polarized Intensity

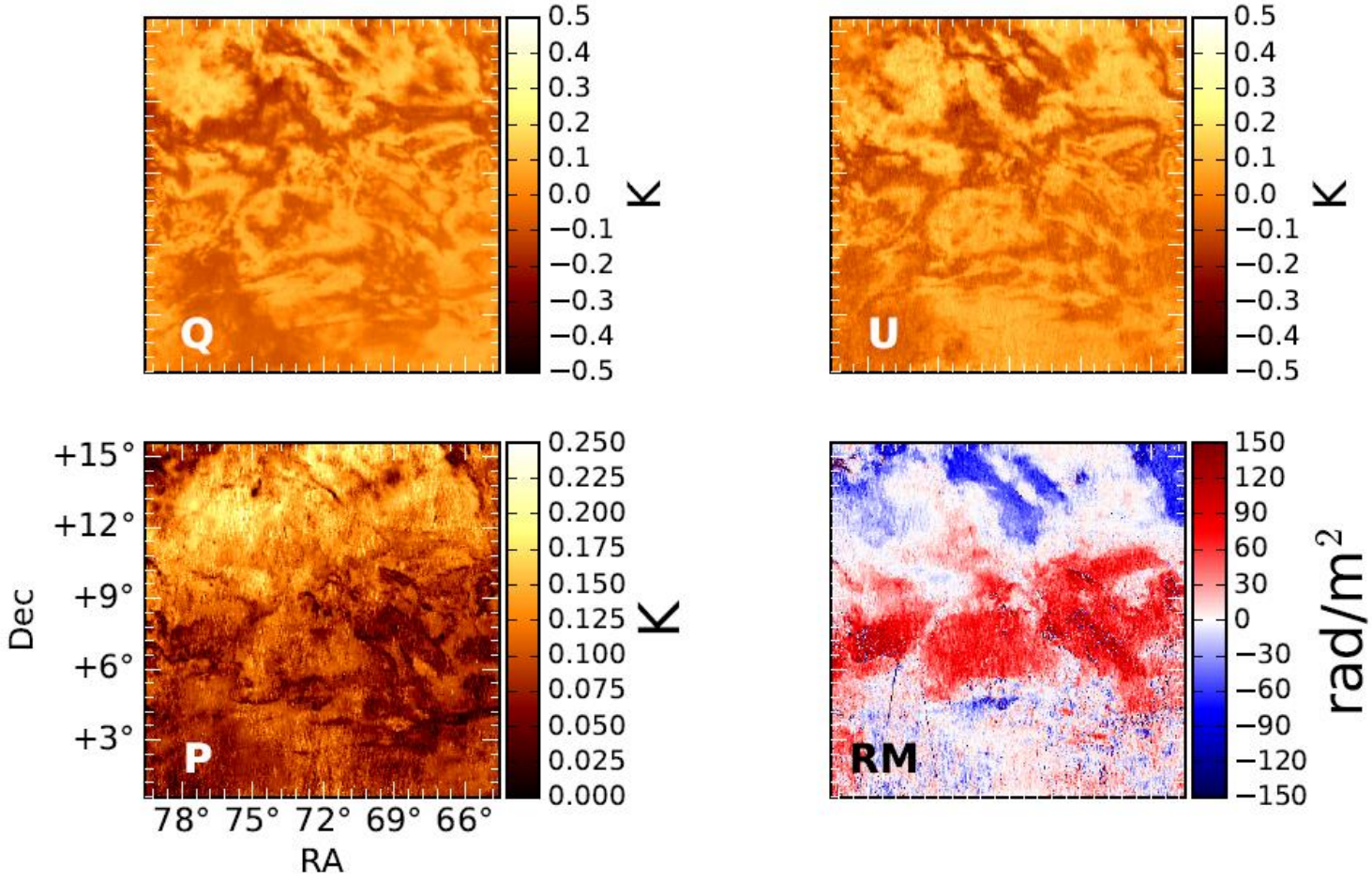


- $PI = \sqrt{Q^2 + U^2} = \sqrt{E^2 + B^2}$
- Advantage: insensitive to variation of position angle (perhaps caused by Faraday rotation)
- Disadvantage: Convolution theorem fails: finite resolution causes depolarization on all angular scales.
- General result: systematically slightly steeper than E,B spectrum.

Extreme PI vs E+B difference:

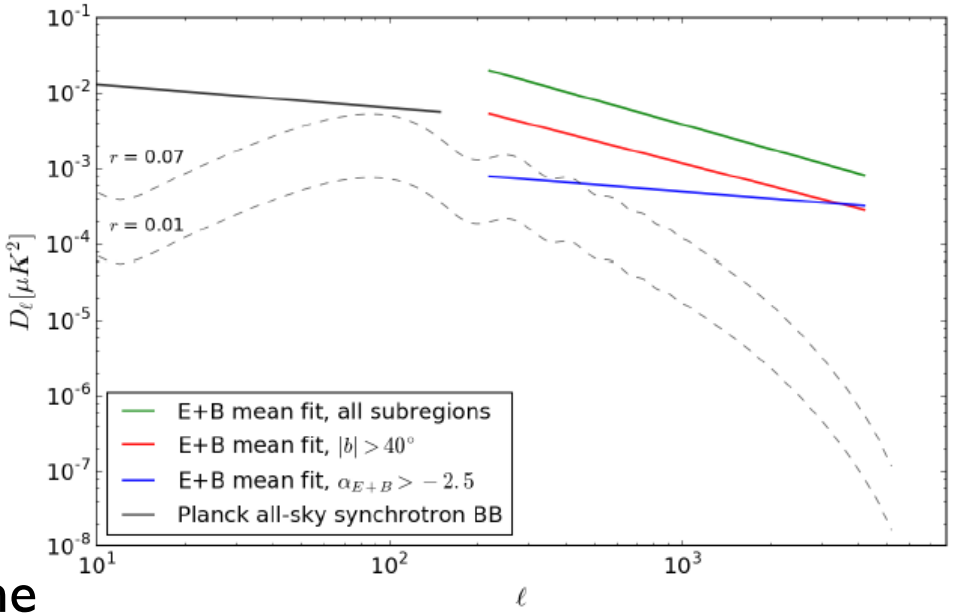


Extreme PI vs E+B difference:



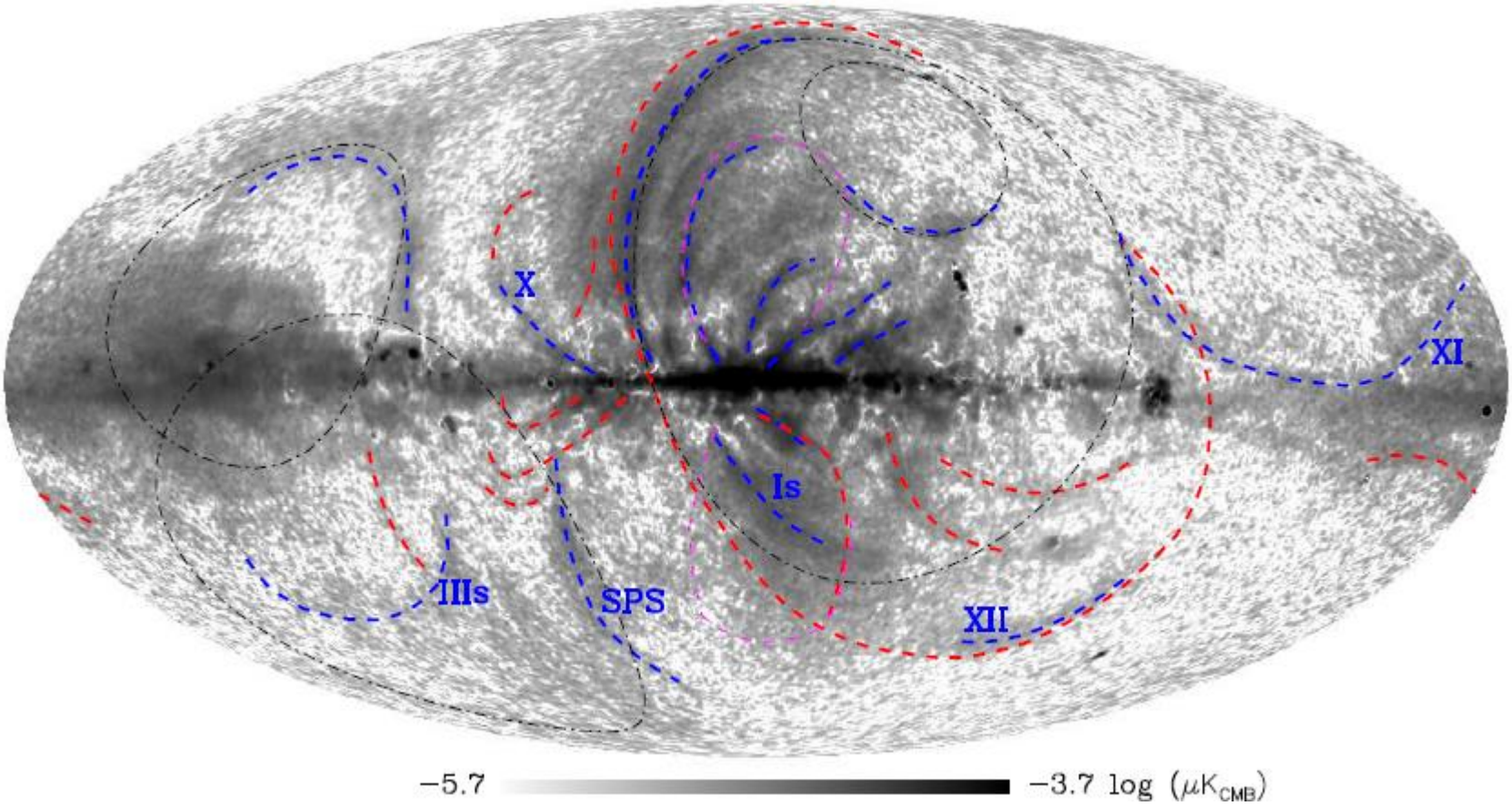
Comparison to CMB B-modes

- Extrapolating mean GALFACTS spectrum to 70 GHz, amplitude is comparable to current limits on CMB B-modes
- Roughly consistent with low-*l* synchrotron spectrum from Planck
- Also roughly consistent with other estimates of the high-*l* spectrum from Parkes.
- Cleanest small patches may allow us to reach *r* = 0.01 for the *l* =80 peak at 70 GHz.



- In practice we need to correct for synchrotron emission at these levels unless observing at > 100 GHz

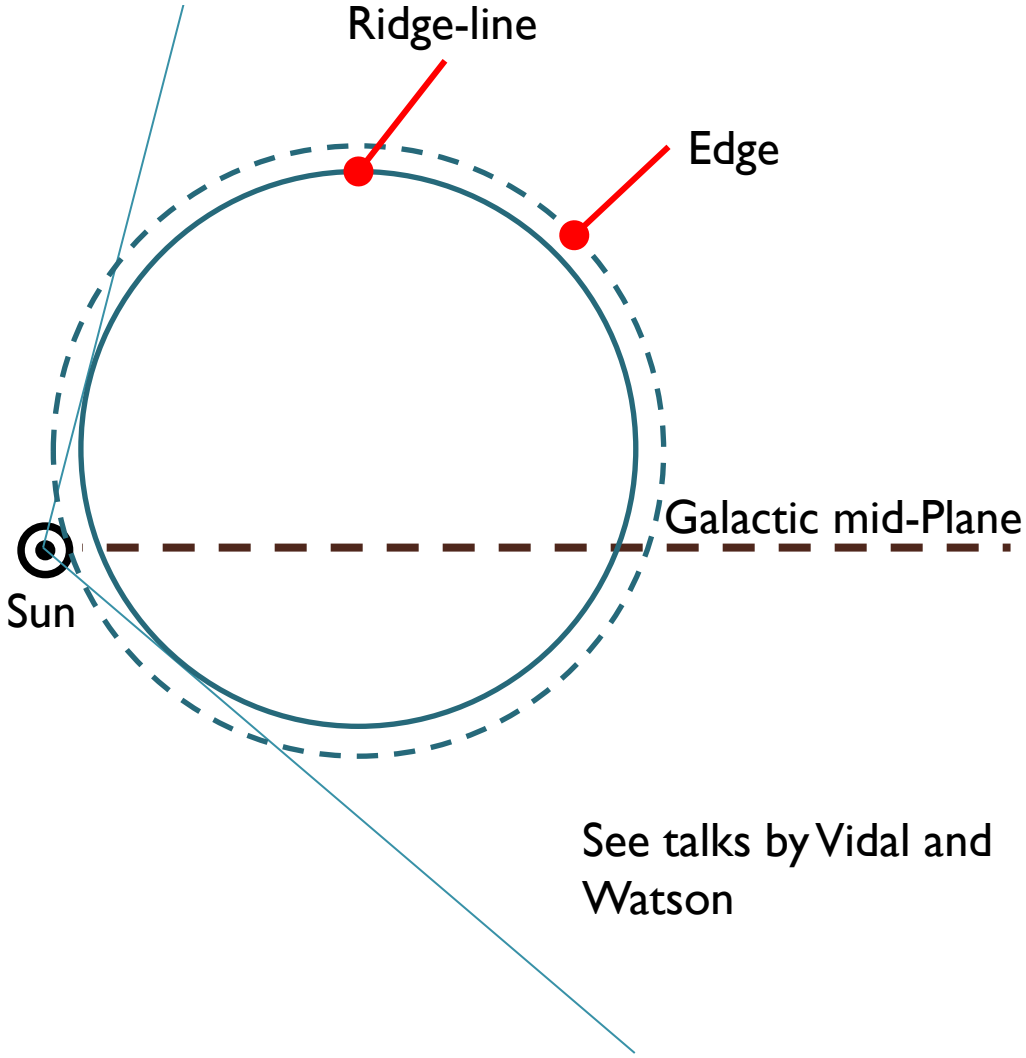
The Polarized sky at 1 cm



Planck+*WMAP* polarized intensity at 28.4 GHz
(log transfer)

Loop I in perspective

- Perspective is very important for such large angular sizes
- Top of observed loop is nowhere near "top" of structure
- No evidence that Loop I is actually a full sphere
  - c.f. the Local Cavity is 'open' at the poles.
- Projected outline south of Galactic plane is not circular

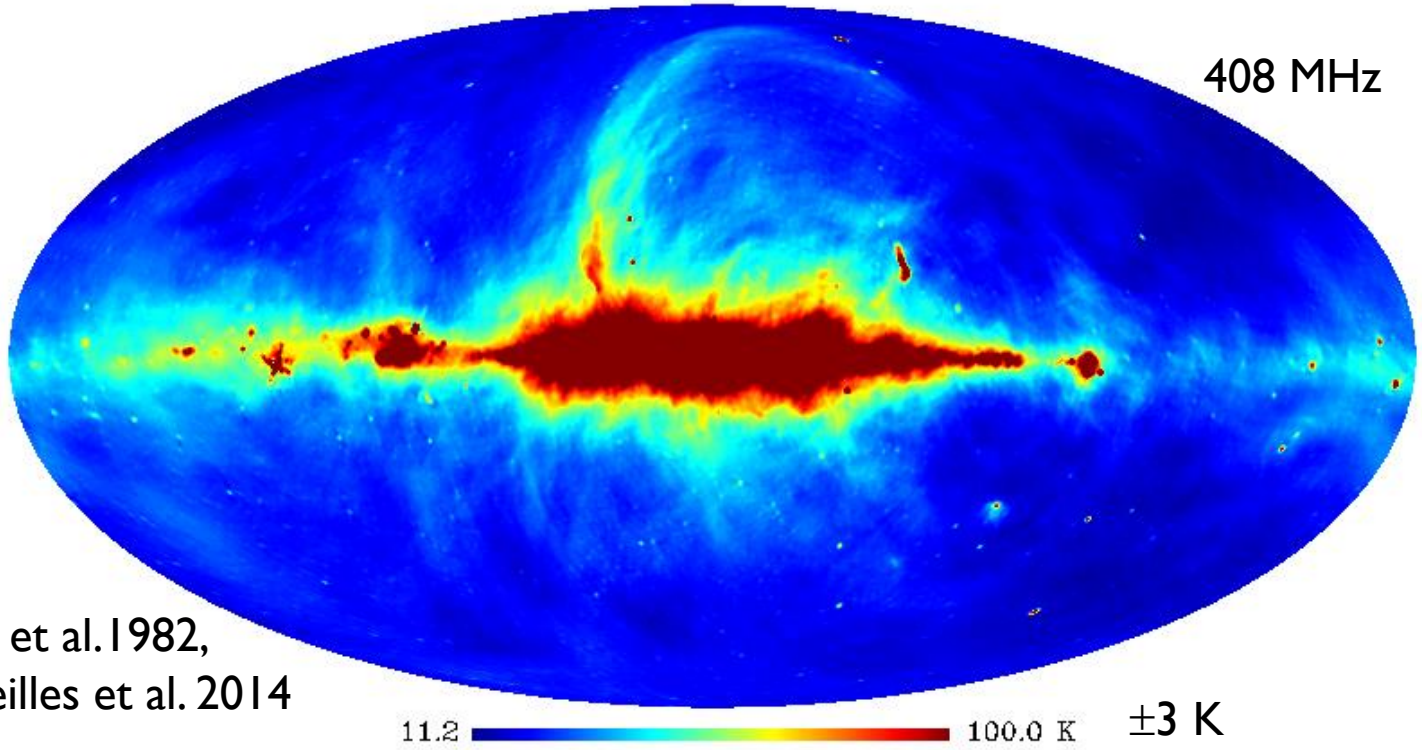


See talks by Vidal and Watson

On zero levels

- No cosmology in $l = 0$ (or 1), so who cares?
- Foreground modelling!
  - $T_B(\nu) = k\nu^{\beta} \neq k\nu^{\beta} - Z(\nu)$
  - Impact of zero-level errors worst in faint sky, i.e. B-mode target regions.
- Single-dish surveys suffer from T_{sys} offset
  - Not a big deal at 100 MHz with $T_{sky} \sim$ kK.
- Interferometers don't see zero level at all.
- Use dedicated single-horn measurements with cryogenic cold reference to get exact values.
  - Or reference to Haslam 408 MHz map
- NB: *Planck*-LFI had cold reference but zero level uncertainty O(100 μK)

High-latitude synchrotron emission

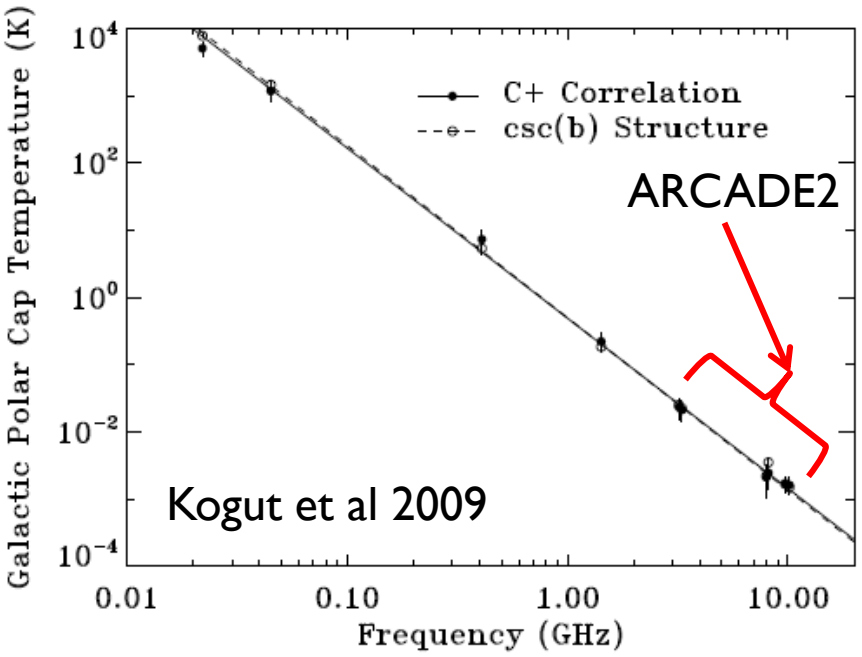


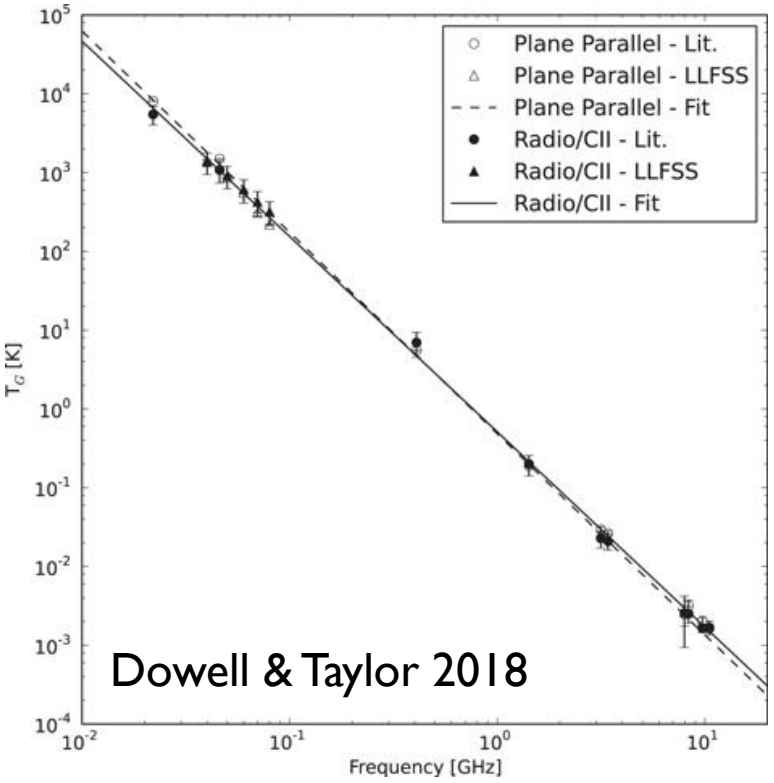
Haslam et al.1982,
Remazeilles et al. 2014

±3 K

- Excess synchrotron emission near Galactic poles first noted by I. S. Shklovsky (*Dokl. Acad. Nauk. SSSR*,**85**,1231, 1952)
- Interpreted as large-scale synchrotron halo around Milky Way
- Major topic of discussion at IAU Symp. 4, *Radioastronomy,* 1955.
- But halos not found in other spiral galaxies…

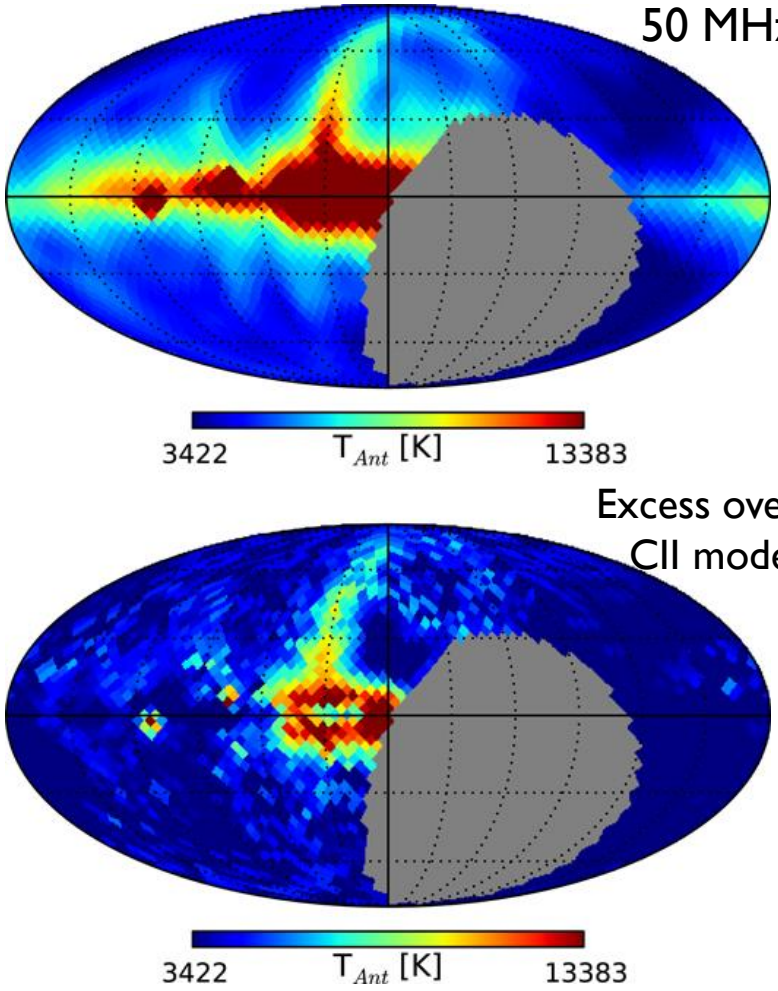
ARCADE2 Offset





Shklovsky/ARCADE Excess

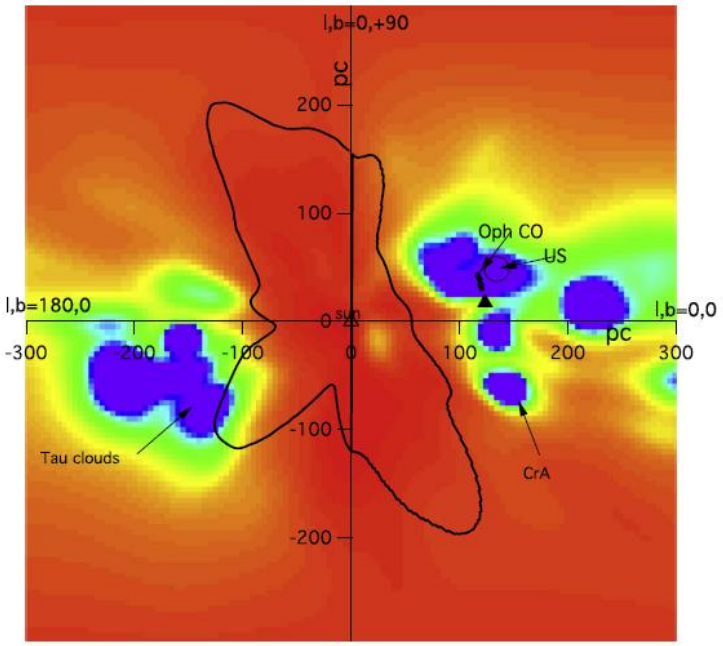
- Fit to plane-parallel (cosec|b|) model, or over Galactic tracer:
  - HI, dust, CII (all of which fit csc|b| quite well as trace thin disk).
- Synchrotron fails
  - Minimum emission at mid latitudes
  - NB Loop I does NOT reach north pole (well defined outer edge).
- But synchrotron does not fit csc|b| + monopole
  - Even excluding loops
- $\Rightarrow$ a LOCAL non-planar component,
  - which certainly has a monopole component.
- $\Rightarrow$ Extragalactic monopole is redundant (Occam's razor).



Dowell & Taylor 2018

Local Hot Bubble (Loop 0?)

- Voyager: B = 4.6 μG just outside heliopause
  - 408 MHz ≡ 1.5 GeV ($\gamma = 3000$)
- Orlando et al., model R:
  - $E^2 N_{e^{+/-}}(E) = 5.0 \times 10^{-3}\ \mathrm{MeV\ m^{-3}}$
- $\Rightarrow T_B(408\ \mathrm{MHz}) = 7\ \mathrm{K}$ @ Galactic poles for100 pc
  - cf. 13.2 K(N) / 14.6(S) K observed
  - Known extragalactic backgrounds subtracted.
- Likely enhanced emission at rim of cavity.



- Liu et al (2018):
  - Outline: from emissivity of ¼ keV X-rays
  - Colours: differential opacity from Lallement et al (2014)

Against ground subtraction

- Most ground-based surveys are affected by significant residual spillover from the ground, which has to be modelled and subtracted:
  - Haslam (indirectly, via Pauliny-Toth & Shakeshaft 1962) – assumed constant with Az.
  - Reich & Reich 1.4 GHz – Assumed constant with Azimuth
  - Wolleben 1.4 GHz polarization
  - GALFACTS 1.4 GHz (Arecibo)
  - GMIMS 1.4 GHz (and lower frequencies)
  - S-PASS
  - C-BASS
- Low frequencies escape, because $T_{\mathrm{sky}} \gg T_{\mathrm{ground}}$

Ground subtraction

- Contribution to received power from the ground depends mainly on intersection of sidelobes with the ground, and therefore on telescope pointing:

$$T_G = T_G(HA, \delta)$$

$$\begin{pmatrix} Q \\ U \end{pmatrix}_G = \boldsymbol{P}_G = \boldsymbol{P}_G(HA, \delta, \Psi)$$

  - Parallactic angle $\Psi = \Psi(HA, \delta)$
  - NB: (HA, δ) maps a.e. one-to-one to (Az, El)
- Other factors are ground temperature and humidity distributions which affect emissivity.
  - Generally subdominant, e.g. little sign of day-night variation in C-BASS ground emission.
- To survey sky, have to observe the full declination range.
- To simplify ground modelling, restrict observation directions to
  - constant HA and/or Az (e.g. meridian transit) (as for Haslam)
  - constant Elevation (as in Reich et al, C-BASS, S-PASS etc).

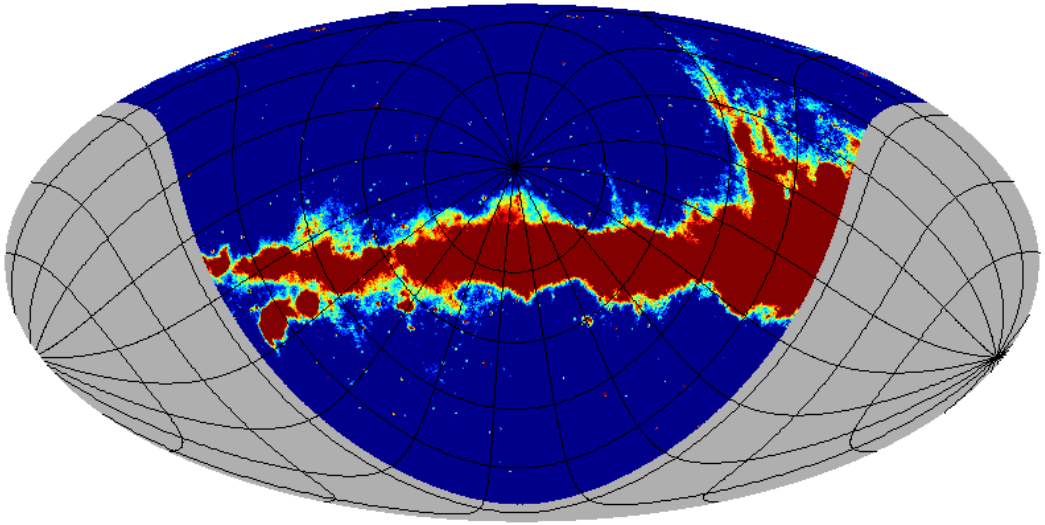
Ground subtraction algorithms

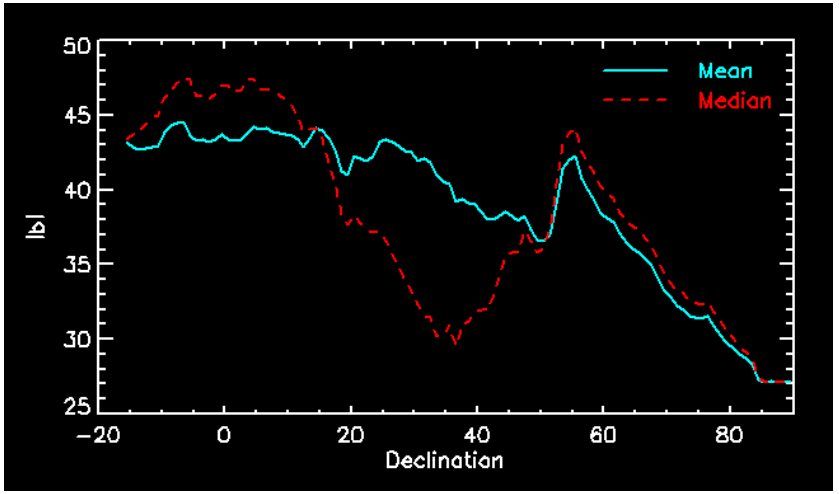
- Simplify, e.g. assume T_G function only of elevation
  - Unfortunately, it isn't.
- Usual procedure:
  - Average signal observed as function of
    - Az (for constant-El scans)
    - Elevation/declination (for meridian transit)
  - Exclude regions of strong emission from average (e.g. Galactic plane, bright point sources etc)
  - Subtract average profile from observed data.

Worries

- What people seem to worry about:
  - How accurately are we subtracting the ground?
  - Controllable: compare day/night, winter/summer, East vs West Azimuths at fixed elevation, different elevations.
  - Allow us to quantify residual uncertainty in ground profile.
- What we should be worrying about:
  - What are we removing from the sky?
  - Answer: we are removing any systematic declination dependence from the 'faint' sky.
  - Does not show up in null tests, if we observe same range of RA at each declination
  - Effect is to null $m = 0$ modes of faint sky.

Example: C-BASS N

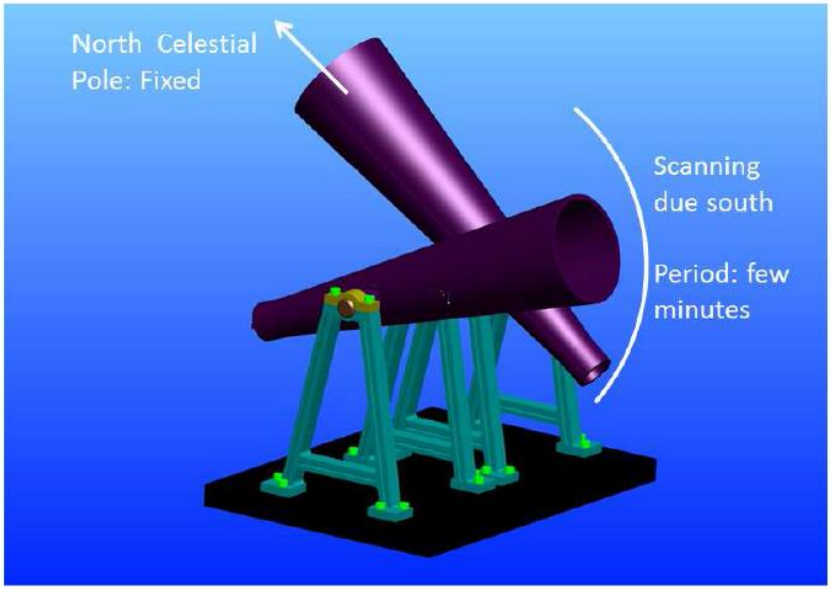




- ‘faint’ sky must include pole to allow ground correction there.
  - Flux cut → 72% of observed sky
- Declination is mildly correlated with Galactic latitude, especially on cut sky.

Advertisement

- L-BASS is a Jodrell Bank project to make an absolutely-calibrated map of the northern sky
  - $\Delta T < 0.1$ K (absolute), 1 mK (relative)
  - FHWM = 20°
  - 1420 MHz (25 MHz BW)
  - RCP only
- Aims:
  - Cross-check ARCADE2
  - Zero levels for GMIMS, GALFACTS…
- Status:
  - Breadboard receiver
  - Horns under construction
  - Observations expected 2019-20.



L-BASS configuration

Advertisement

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